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Optical Spectra from Highly Charged Ions

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Abstract

Optical spectra of Ne, Ar and Kr have been excited in an electron beam ion trap (EBIT). A prism spectrograph was used for broad band (3700–6000 Å) spectral surveys with moderate resolution to establish the excitation thresholds and thus the charge states of transitions in highly charged ions. A high-resolution transmission grating spectrometer for high precision measurements yielded detailed spectra. The "inverted trap" technique was employed for *in situ* wavelength calibrations.

1. Introduction

Along isoelectronic sequences, the transition energies of given transitions usually increase rapidly. Therefore the lines that in neutral atoms of the light elements appear in the visible spectrum are in the vacuum ultraviolet for moderately high charge state ions, and in the extreme ultraviolet for highly charged ones. However, highly charged ions (HCI) still feature optical spectra, but these relate to transitions that are less familiar to classical spectroscopy. Consequently, the atomic data for optical transitions, especially for ions with charges higher than 3+, are largely unknown. In fact, most lines have never been identified. Using the extensive range of spectroscopic facilities on the LLNL EBIT-II device, we are cataloguing spectral lines from HCI, such as neon, argon and krypton, in the optical region. The present work continues earlier measurements of krypton, xenon and barium [1] at the Livermore EBITs.

2. Experiment

For broad-band spectral surveys (3700–6000 Å), we employed a Steinheil glass prism spectrograph. With $f/4$ coupling lenses, much of the visible spectral range was being imaged within a field of 25 mm, the width of our scientific-grade 1024×1024 pixel CCD camera. The dispersion of the prism is very non-linear: at 4000 Å it is about 1.28 Å/pixel, and it increases up to 4.80 Å/pixel at 5500 Å. The resolving power of the spectrometer varies from 300 to up to 1000. Sets of spectra were recorded at various electron beam energies, from about 150 eV up to 17 keV, for Ne, Ar and Kr. One of these gases at a time was injected continuously into the EBIT, using a differentially pumped gas injector. The ion trap was frequently purged (by appropriate lowering of drift tube voltages) to prevent the build-up of heavy-element contaminants.

Unlike earlier studies, which used low-pressure discharge lamps [2], the wavelength calibration of the spectrometer was performed using the "inverted trap" mode, that is, without any change of geometry, simply removing the potential that is normally applied to the top drift tube. In this mode, highly charged ions are expelled from the trap, while the electron beam and the injected gas flow interact for a long enough time to excite neutral atoms and to produce singly and doubly charged ions. For these, precise reference data are available [3]. Shown in Fig. 1 is a spectral image comparison of the "electron trapping" mode (Fig. 1(b)) with the inverted trap mode (Fig. 1(c)), along with line-outs of the same spectra. In the inverted trap mode, the length of each line (the image of the emitting ion cloud spread out along the drift tube axis) is about half the length of that in the trapping-mode. This is because in the inverted-trap mode, the ion cloud represents the actual intersection of the electron beam with the expanding gas stream from the injector, while in the electron trapping mode, ions are moving in the confines of the whole drift tube region. In the line-outs of the spectral images, Fig. 1(a) for the trapping mode and Fig. 1(d) for the inverted trap mode, one can see that many of the calibration lines persist even in the trapping mode (a fact that has been noted in [4]). The shorter length of their line images in the spectrogram attests to their low charge state.

Example prism spectra are shown in Fig. 2 for elements N (top) and Ne (bottom) at one electron beam energy, and in Fig. 3 for Ar at various electron beam energies. A number of strong lines and their identifications are marked in the figure. The bulk of the spectral lines is associated with

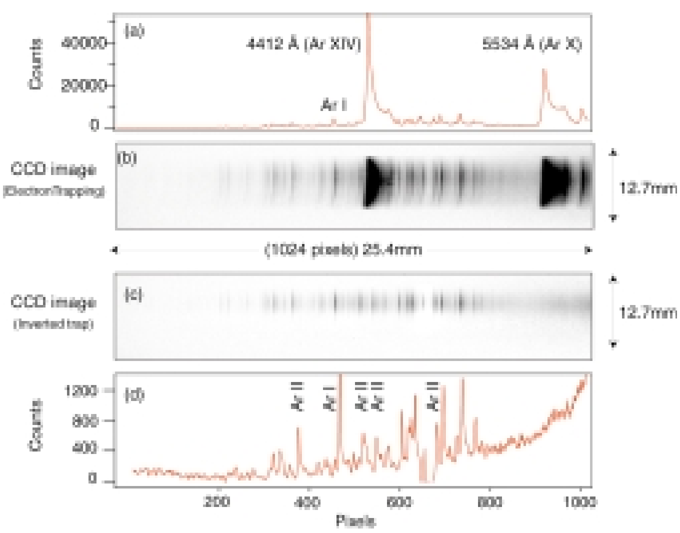

Fig. 1. Spectral images and line-outs showing regular trap operation (a,b) and the *inverted trap* mode (c,d) with Ar gas injected into EBIT. With the trap voltages set for trapping, the spectrum is dominated by magnetic dipole (M1) transitions.

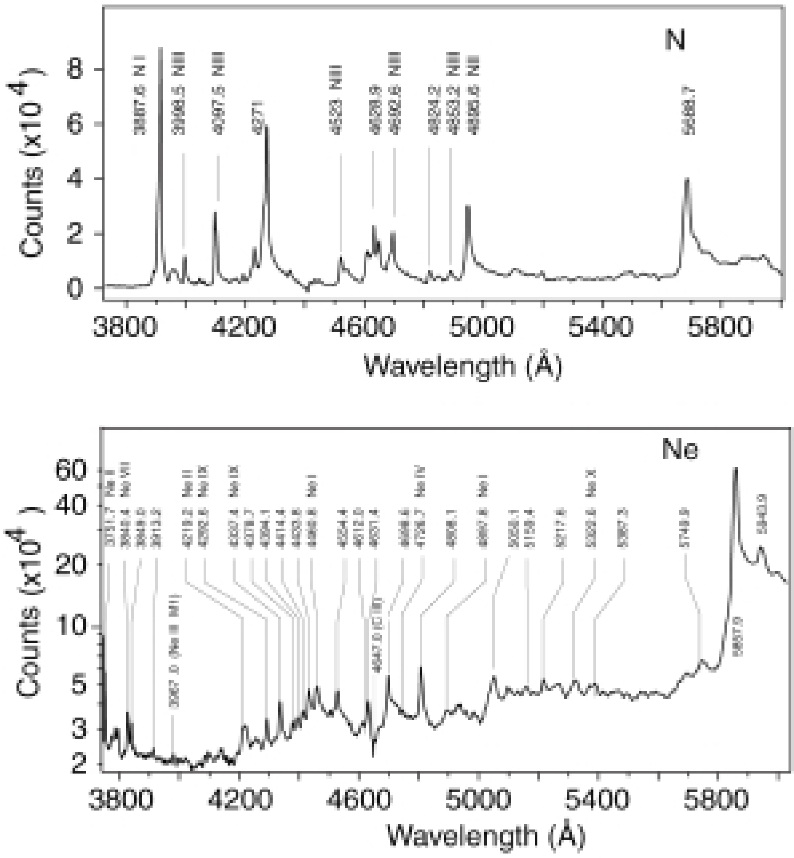

Fig. 2. Spectra of N and Ne obtained with the prism spectrograph. The most prominent lines are given with approximate wavelengths. Both spectra contain a fair number of unidentified lines.

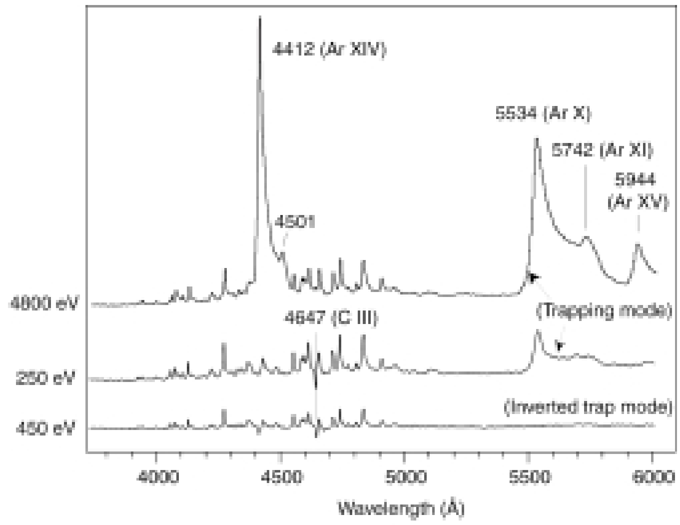

Fig. 3. Spectra of Ar obtained with the prism spectrograph. A line of C III appears as a negative line, because it had been present in background spectrum (no gas injection) that was subtracted from the data with gas injection. The inverted-trap spectrum at 450 eV electron beam energy (bottom trace) largely contains the same lines as a low-energy trapping mode spectrum. The M1 transitions in Ar X, Ar XIV and Ar XV originate from ions with production thresholds between 400 eV and 1 keV and evidently persist up to much higher electron beam energies. The transition rates of all three forbidden transitions of Ar have been measured in a separate experiment [10]. The Ar X line appears in the 250 eV spectrum, that is below its nominal threshold, because of less well determined electric field distributions in low-energy EBIT operation and the energy width of the electron beam.

low-charge state ions; as a matter of fact, about 130 lines of Ne and Ar were observed from low charge states [3]. Over half of the lines have not been reported before.

At higher electron beam energies, a few very intense lines appear. These are recognized as magnetic dipole transitions between low-lying levels of highly charged ions [6]. For example, eight such lines from Ar [5] and ten from Kr [7] were observed using the prism spectrometer. Shown in Fig. 3 are the predominant M1 transitions from Ar XIV at 4412 Å and Ar X at 5534 Å. Some of these lines, such as Ar X and Kr XXIII, are known from the solar corona or from tokamak plasmas. These lines offer access to highly charged ions as probes for hot plasma conditions by the versatile optical instruments that are available for the visible range. The appearance thresholds in our spectra reveal the respective ion charge states, which makes identification easier.

Based on the survey spectra, high-resolution measurements over narrower regions of interest were made using a high-resolution transmission grating spectrometer (TGS) that has a resolving power of about 15000 [8,9]. For example, Kr spectra in the region from 3450 Å to 3900 Å have been measured with a wavelength resolution that is over an order of magnitude higher than that afforded by the prism spectrometer [9]. Figure 4 shows the comparison spectra of Kr at the same electron beam energy between the prism spectrometer (top) and the TGS (bottom). Again, calibration spectra were readily available from recordings with an inverted trap as well as from some low-charge state reference lines that also appeared under high-energy con-

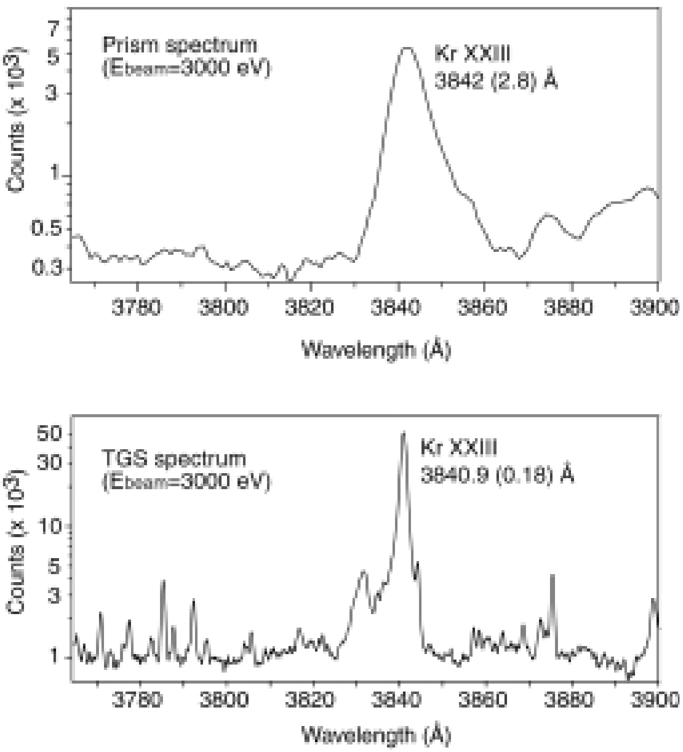

Fig. 4. Comparison spectra of Kr obtained with the prism spectrograph (top) and the transmission grating spectrometer (TGS) (bottom). The strong Kr line in the spectrum is from an M1 transition in the ground configuration of the Si-like ion Kr^{22+} that has also been studied for its transition rate [11].

ditions. Owing to the high efficiency and the much higher resolving power of the transmission grating spectrometer in comparison to the prism spectrometer, a great deal more lines were observed. Spectra of Ne, Ar and Kr taken with this spectrometer are shown in Fig. 5.

Acknowledgement

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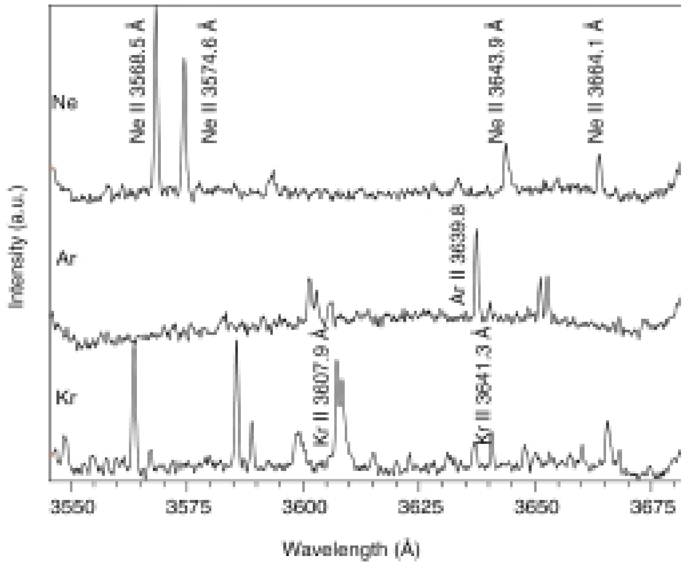

Fig. 5. High-resolution spectra of Ne, Ar and Kr at an electron beam energy of 2 keV as recorded with the transmission grating spectrometer.

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